THE ASTROPHYSICAL JOURNAL, 659: L161–L164, 2007 April 20

A NEW TYPE OF EXTREMELY METAL-POOR STAR[1]

JUDITH G. COHEN,[2] ANDREW MCWILLIAM,[3] NORBERT CHRISTLIEB,[4] STEPHEN SHECTMAN,[3]
IAN THOMPSON,[3] JORGE MELENDEZ,[5] LUTZ WISOTZKI,[6] AND DIETER REIMERS[7]
Received 2007 February 3; accepted 2007 March 13; published 2007 March 20

ABSTRACT

We present an abundance analysis for the extremely metal-poor (EMP) star HE 1424−0241 based on high-dispersion spectra from HIRES at Keck. This star is a giant on the lower red giant branch with [Fe/H] ~ -4.0 dex. Relative to Fe, HE 1424−0241 has normal Mg, but it shows a very large deficiency of Si, with $\epsilon(\mathrm{Si})/\epsilon(\mathrm{Fe}) \sim 1/10$ and $\epsilon(\mathrm{Si})/\epsilon(\mathrm{Mg}) \sim 1/25$ that of all previously known EMP giants or dwarfs. It also has a moderately large deficiency of Ca and a smaller deficit of Ti, combined with enhanced Mn and Co and normal or low C. We suggest that in HE 1424−0241 we see the effect of a very small number of contributing supernovae, and that the SNe II contributing to the chemical inventory of HE 1424−0241 were biased in progenitor mass or in explosion characteristics so as to reproduce its abnormal extremely low Si/Mg ratio. HE 1424−0241 shows a deficiency of the explosive α-burning elements Si, Ca, and Ti coupled with a ratio [Mg/Fe] normal for EMP stars; Mg is produced via hydrostatic α-burning. The latest models of nucleosynthesis in SNe II fail to reproduce the abundance ratios seen in HE 1424−0241 for any combination of the parameter space of core-collapse explosions they explore.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — supernovae: general

1. INTRODUCTION

Extremely metal-poor (EMP) stars provide important clues to the chemical history of our Galaxy: the role and type of early supernovae (SNe), the mode of star formation in the proto–Milky Way, and the formation of the Galactic halo. The classes and properties of EMP stars are summarized by Beers & Christlieb (2005). The peculiarities discussed there revolve around enhancements of the elements C and N, which are often accompanied by enhancements of the neutron capture elements beyond the Fe peak. Mass transfer within a binary system that occurred while the former primary was an asymptotic giant branch (AGB) star is an explanation widely suggested for the majority of these peculiarities, including excesses of both CNO and heavy *s*-process neutron capture elements (see, e.g., Cohen et al. 2006).

The number of EMP stars known below [Fe/H] −3.5 dex is very small.[8] We have been trying to increase it through data mining of the Hamburg/ESO Survey (HES; Wisotzki et al. 2000). In this Letter, we report our discovery of an EMP star that shows peculiarities in its chemical abundance distribution not seen in any other such star to date that is known to the authors.

2. STELLAR PARAMETERS AND ANALYSIS

HE 1424−0241 (R.A. = $14^{\mathrm{h}}26^{\mathrm{m}}40.3^{\mathrm{s}}$, decl. = $-02°54'28''$; J2000.0) was observed in 2004 May with the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) at the Keck I telescope. Based on this high-resolution spectrum, whose total exposure time was 3600 s, it was recognized at that time as an interesting EMP star with very low Fe metallicity. It was observed again with HIRES in 2006 April after the detector upgrade with a total exposure time of 6000 s. This yielded wider spectral coverage extending far into the UV and a better signal-to-noise ratio than the original data.

To determine stellar atmosphere parameters, we use the procedures described in Cohen et al. (2002) and adopt in all subsequent work by our 0Z project published to date. Our T_{eff} determinations are based on broadband colors $V-I$, $V-J$, and $V-K$. The IR photometry is taken from the Two Micron All Sky Survey (Skrutskie et al. 2006; Cutri et al. 2003). We have obtained new photometry at V and at I for HE 1424−0241 ($V = 15.45 \pm 0.03$ mag and $I = 14.54 \pm 0.03$ mag) from ANDICAM images taken for this purpose over the past 2 years via a service observing queue on the 1.3 m telescope at Cerro Tololo Inter-American Observatory operated by the Small and Moderate Aperture Research Telescope System consortium.[9] We derive surface gravities through combining these T_{eff} with an appropriate 12 Gyr isochrone from the grid of Yi et al. (2001). We thus derive $T_{\mathrm{eff}} = 5195$ K and $\log g = 2.50$ dex. The narrow Balmer lines do not permit the star to be a dwarf below the main-sequence turnoff.

The abundance analysis was carried out in a manner similar to those described in Cohen et al. (2004). Full details will be given in an upcoming paper, which will present the most metal-poor stars we have found thus far. If T_{eff} for HE 1424−0241 were to be increased by 100 K, the deduced [Fe/H] would increase by 0.15 dex, but the abundance ratios [X/Fe] would be essentially unchanged.

[1] Based in part on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration.

[2] Palomar Observatory, California Institute of Technology, Pasadena, CA 91125; jlc@astro.caltech.edu.

[3] Carnegie Observatories of Washington, Pasadena, CA 91101; andy@ociw.edu, shec@ociw.edu, ian@ociw.edu.

[4] Current address: Department of Astronomy and Space Physics, Uppsala University, 75120 Uppsala, Sweden; formerly at Hamburger Sternwarte, Universität Hamburg, D-21029 Hamburg, Germany; norbert@astro.uu.se.

[5] Palomar Observatory, California Institute of Technology, Pasadena, CA 91125. Current address: Australian National University, Australia; jorge@mso.anu.edu.au.

[6] Astrophysical Institute Potsdam, D-14482 Potsdam, Germany; lwisotzki@aip.de.

[7] Hamburger Sternwarte, Universität Hamburg, D-21029 Hamburg, Germany; dreimers@hs.uni-hamburg.de.

[8] The standard nomenclature is adopted; the abundance of element X is given by $\epsilon(\mathrm{X}) = N(\mathrm{X})/N(\mathrm{H})$ on a scale where $N(\mathrm{H}) = 10^{12}$ H atoms. Then $[\mathrm{X/H}] = \log[N(\mathrm{X})/N(\mathrm{H})] - \log[N(\mathrm{X})/N(\mathrm{H})]_{\odot}$, and similarly for [X/Fe].

[9] See http://www.astronomy.ohio-state.edu/ANDICAM and http://www.astro.yale.edu/smarts.

TABLE 1
Abundances for HE 1424−0241

Species	log ϵ(X) (dex)	[X/H] (dex)	[X/Fe] (dex)	σ (dex)	Number of Lines	[X/Fe] (0Z)[a] (dex)	[X/Fe] (VLT)[b] (dex)
C	<5.26	<−3.33	<0.62	…	CH	…	∼0.20
N	<5.10	<−2.83	<1.12	…	NH	…	…
Na i[c]	2.32	−4.00	−0.05	0.07	2	−0.15	−0.20
Mg i	4.03	−3.51	0.44	0.12	3	0.49	0.24
Al i[d]	2.35	−4.13	−0.18	0.15	2	−0.13	−0.12
Si i	2.59	−4.96	−1.01	…	1	0.45	0.41
Ca i	1.84	−4.52	−0.58	…	1	0.32	0.27
Ca ii	2.10	−4.26	−0.31	…	1	…	…
Sc ii	−0.95	−4.05	−0.10	…	1	0.13	0.04
Ti ii	0.85	−4.14	−0.17	0.17	8	0.29	0.24
V ii	<0.64	<−3.36	<0.59	…	1	…	…
Cr i	1.33	−4.34	−0.38	0.09	5	−0.45	−0.46
Mn i[e]	1.59	−3.80	0.15	0.02	2	−0.42	−0.47
Mn ii	1.69	−3.70	0.25	0.13	2	…	…
Fe i	3.49	−3.96	0.00	0.18	39	0.00	0.00
Fe ii	3.58	−3.87	0.09	0.22	4	0.00	0.00
Co i	1.98	−2.94	1.01	0.21	4	0.50	0.40
Ni i	2.52	−3.73	0.22	0.01	2	−0.08	−0.04
Cu i	−0.41	−4.62	−0.67	…	1	…	…
Sr ii	<−2.75	<−5.65	<−1.70	…	2	…	…
Y ii	<−1.46	<−3.70	<0.25	…	2	…	…
Ba ii[f]	−2.74	−4.87	−0.92	…	1	…	…
Eu ii	<−1.95	<−2.46	<1.49	…	1	…	…

[a] Regression lines for C-normal giants from our 0Z survey, evaluated at −4.0 dex.
[b] Regression lines from Cayrel et al. (2004, Table 9), evaluated at −4.0 dex.
[c] Non-LTE correction of −0.2 dex has been applied for [Na/Fe] from the Na D lines.
[d] Non-LTE correction of 0.6 dex has been applied for [Al/Fe] from the 3950 Å doublet.
[e] The adjustment of 0.4 dex for the 4030 Å Mn i triplet suggested by Cayrel et al. (2004) and by our own work has been applied here.
[f] The Ba ii line at 4554 Å is only marginally detected, and therefore the Ba abundance may also be interpreted as an upper limit.

3. ABUNDANCES IN HE 1424−0241

The abundances we derive for HE 1424−0241 are given in Table 1. The number of lines used and the σ of the derived log ϵ(X) are given for each species for which absorption lines could be detected; upper limits for some key elements are included. These results are compared to the evaluation at [Fe/H] −4.0 dex of linear fits to the abundance ratios determined by our 0Z project of stars from the HES from the 0Z project (many still unpublished) with $T_{\rm eff} < 6000$ K and without substantial carbon enhancement ([C/Fe] < 1.0 dex). In the last column of the table, we give the same as determined by Cayrel et al. (2004) for EMP giants. The dispersion about their regression lines for giants with −4.2 dex < [Fe/H] < −3.1 dex is small, only 0.11 dex for Mg, 0.20 dex for Si, and 0.11 dex for Ca. The extremely good agreement between the abundance ratios for EMP stars found by these two independent large survey projects, our 0Z project and the First Stars VLT project, and listed in the table is very gratifying and provides support for our statements about the extreme peculiarities of HE 1424−0241.

The anomalies seen in HE 1424−0241 are many. The most extreme and most peculiar is the very large deficit of Si, with [Si/Fe] ∼ −1.0 dex and [Si/Mg] ∼ −1.4 dex, while all other known EMP stars have [Si/Fe] ∼ 0.3 dex and [Si/Mg] ∼ −0.3 dex. [Si/Fe] is low in HE 1424−0241 by more than 6 σ compared to all other known EMP giants,[10] as is shown in Figure 1. HE 1424−0241 also has a moderately large deficiency of Ca (significant at the 5 σ level) and a smaller deficit of Ti. It has enhanced Mn and strongly enhanced Co (significant at the 4 σ level), both odd atomic number elements. Copper (another odd atomic number Fe-peak element) may also be enhanced, but the single detected line is the rarely observed resonance line at 3274 Å. Carbon is not enhanced, and the heavy neutron capture elements Sr and Ba have low abundances relative to Fe, suggesting that mass transfer in a binary system involving an AGB star is not the cause of the peculiar abundance ratios found in HE 1424−0241. Each of these anomalies is seen in both the 2004 May and 2006 April HIRES spectra. For example, the equivalent width of the only detected Si i line (at 3905 Å) is 17.7 mÅ from the 2004 spectrum and 13.9 mÅ from the latter one.

No other EMP star shows the low Si/Fe and Ca/Fe ratios seen in HE 1424−0241. With one minor exception, no other EMP dwarf or giant that is not C-enhanced is known to show highly statistically significant abundance ratio deviations for any elements between Mg and Ni. (C-enhanced EMP stars sometimes show large enhancements of the light elements: for example, CS 22949−037, found by McWilliam et al. 1995, analyzed again by Depagne et al. 2002.) The exception is the dwarf HE 2344−2800 with [Fe/H] ∼ −2.7 dex, found in the Keck Pilot Project (Cohen et al. 2002; Carretta et al. 2002) to have an excess of Mn, with ϵ(Mn)/ϵ(Fe) approximately twice the prevailing value among EMP stars. This has been confirmed by a better HIRES spectrum acquired in 2004; this dwarf also has a small excess of Ti relative to Fe. A few C-normal EMP stars (CS 22169−035 and CS 22952−015, for example, both of which are included in Fig. 1), have slightly low α-elements, but, as the figure clearly illustrates, in no case do they approach the anomalies seen in HE 1424−0241.

4. COMPARISON WITH PREDICTED SN II YIELDS

At least several SNe contribute to the chemical inventory of stars with [Fe/H] ≳ −3 dex, and the observed ratios of the

[10] Here σ is the sum in quadrature of the uncertainty in [X/Fe] for HE 1424−0241 and that of the uncertainty of the linear regression for the "normal" EMP giants.

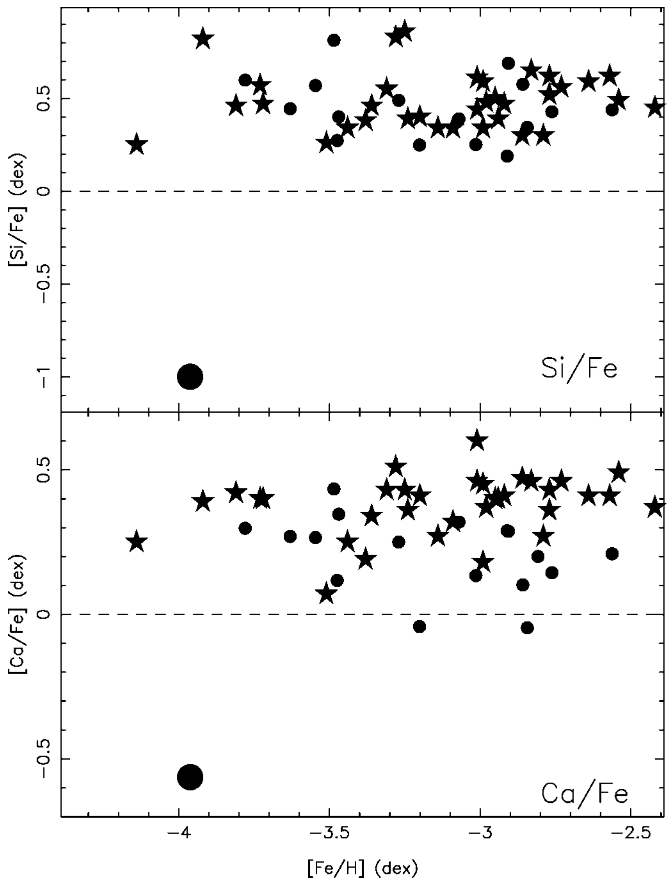

FIG. 1.—[Si/Fe] (*upper panel*) and [Ca/Fe] (*lower panel*) are shown as a function of [Fe/H] for EMP giants with [Fe/H] < -2.4 dex. Filled circles denote HES stars from our 0Z project, and star symbols are giants from the First Stars VLT project (Cayrel et al. 2004). HE 1424−0241 is shown as the large filled circle and is the only outlier, being very low in both panels. The dashed horizontal lines represent the solar abundance ratios.

chemical elements are determined by a sum over an assumed initial mass function of predicted SN II yields. SNe Ia and AGB stars also contribute at still higher metallicity and later times. But given the very low metallicity of HE 1424−0241, ejected material from only a very small number of core-collapse SNe are presumed to have contributed to the material in this star. We must therefore find a model SN II whose predicted nucleosynthetic yields match the abundance ratios seen in this star. ^{28}Si is formed largely in regions interior to where the bulk of the ^{24}Mg is produced, although of course nothing of either of these species remains in the central region of the SN, which is mostly ^{56}Ni. Thus, the details of the SN explosion model are important in determining the Si/Mg ratio in the ejected material. We require a range in the ratio of ^{28}Si/^{24}Mg in the ejected material of at least a factor of 10 to reproduce the behavior both of HE 1424−0241, with its strong deficit of explosive α-burning elements but normal Mg (from hydrostatic α-burning), and of all previously known "normal" EMP stars.

The older models of Woosley & Weaver (1995) are much more effective at reproducing the observed distribution of abundance ratios in HE 1424−0241. Mg/Si production varies by a factor exceeding 10 in these models, with Mg yields highest at masses near 35 $M_{\odot}$, while Si yields reach their maximum in SNe II with lower progenitor masses near 20 $M_{\odot}$. These yields can qualitatively reproduce the behavior seen in HE 1424−0241.

However, none of the SN II models in the grids recently calculated by Chieffi & Limongi (2004) and by Tominaga et al. (2007) come close to reproducing the abundance ratios among the α-elements seen in HE 1424−0241. Both studies provide predictions of explosive yields for SN II progenitors with a wide range of initial masses from 13 to 35 or 50 $M_{\odot}$ with a wide range of metallicities. They included an extensive network of nuclear reactions. For the mass cut adopted in each of these two studies, they each predict yields after the radioactive decays for ^{28}Si/^{24}Mg whose range over the entire set of model explosions does not exceed a factor of 2. However, the two studies differ in which mass range of SN progenitors produces larger ratios of ^{28}Si/^{24}Mg, Chieffi & Limongi (2004) favoring lower mass progenitors and Kobayashi et al. (2006) suggesting progenitor masses at the upper end of the range they consider. In no case does the predicted production ratio [Si/Fe] become less than −0.1 dex.

The most recent predictions of nucleosynthesis yields in SNe II have undoubtedly been tuned to reproduce the behavior of the previously known EMP stars with [Fe/H] reaching down to ∼−4 dex. The abundance ratios we have derived for HE 1424−0241, however, demonstrate that these models do not reproduce the full range of the behavior of nucleosynthesis achieved in real SNe II and seen among the most peculiar of the large sample of EMP stars we have studied in the 0Z project.

Production of the odd atomic number elements Mn and Co occurs through incomplete Si-burning for Mn and complete Si-burning for Co. Kobayashi et al. (2006) point out that the odd-to-even ratio among the Fe-peak elements depends on the mixing-fallback process, the explosion energy, and the neutron excess Y_e. While again no published model can reproduce the large excess of Co and Mn relative to Fe seen in HE 1424−0241, we must hope that some combination of these parameters can be found that will accomplish this task.

5. BEHAVIOR OF THE α-ELEMENTS

Differential analyses of large samples of stars within a small range of T_{eff} in the thin disk of the Galaxy as compared to stars in the thick disk such as those of Edvardsson et al. (1993), Bensby et al. (2004), and Reddy et al. (2006) have been able to achieve very high precision. These surveys have demonstrated that the trends of [X/Fe] versus [Fe/H] are not identical between the various stellar populations of the Galaxy. But in such studies to date, all the α-elements are believed to have varied together and to show the same trends.

A few moderately metal-poor halo field stars have been found that appear to be α-poor; Fulbright (2002) suggests that lower [α/Fe] stars are found among those with high space velocities with respect to the local standard of rest, while Stephens & Boesgaard (2002) suggest such stars are associated with the outer halo. The most extreme α-poor stars, including that found by Carney et al. (1997), were reviewed by Ivans et al. (2003). However, these stars show depletions of Na, Al, Mg, Si, and Ca with respect to Fe. They are sufficiently metal-rich compared to HE 1424−0241 that their chemical inventory has a composite origin, with SNe Ia, SNe II, and AGB stars all contributing, and can be qualitatively explained by varying the SN Ia/SN II ratio, an explanation that cannot be applied to HE 1424−0241.

All this, while interesting, is not the key issue for the abundance distribution of the EMP giant HE 1424−0241. Woosley & Weaver (1995) find that Si, Ca, and Ti are formed by explosive α-burning in SNe II, while O and Mg are produced by hydrostatic α-burning. HE 1424−0241 shows a clear large deficiency of the former elements but no apparent deficiency of the hydrostatic α-burning element Mg.

As abundance analyses have reached higher levels of accuracy (or at least of internal accuracy) and as sample sizes have increased, there have been reports of small differences, much smaller than those we find in HE 1424−0241, between the behavior of the explosive and hydrostatic α-elements in certain specific environments. The recent analyses of Fulbright et al. (2007) of a sample of 27 red giants with Keck HIRES spectra in Baade's window in the Galactic bulge found that the explosive α-elements Si, Ca, and Ti have similar trends of [X/Fe] as a function of [Fe/H]. However, they found that the hydrostatic α-elements O and Mg show a different behavior in the bulge giants. This separation within the Galactic bulge sample is small; ∼0.2 dex in total, much smaller than what we observe in HE 1424−0241.

Fulbright et al. (2007) detected similar effects, again on a much smaller scale than in HE 1424−0241, in a second environment, among stars in the Milky Way dwarf spheroidal satellite galaxies. They used the compilation of data from the literature by Venn et al. (2004), which relies heavily on the work of Shetrone (see, e.g., Shetrone et al. 2003).

These examples demonstrate that the production ratios of the explosive to hydrostatic α-elements are not fixed; they must depend on environment, the initial mass function, the star formation history, or other relevant factors. The subtle differences seen in the Galactic bulge and in dSph giants between the behavior of these two groups of α-elements, with the explosive α-elements being more depleted than the hydrostatic ones, are seen in a much more dramatic fashion in HE 1424−0241. HE 1424−0241 is a very extreme example of this phenomenon in a situation where only a very few SNe contributed to the chemical inventory of this star and where, because of the very low metallicity of HE 1424−0241, most other possible explanations for this become irrelevant.

6. SUMMARY

All C-normal EMP giants studied to date in the two major surveys, our 0Z project (Cohen et al. 2004) and the First Stars VLT project (Cayrel et al. 2004), show smooth trends of abundance ratios [X/Fe] with Fe metallicity with modest dispersion around these trends and no strong outliers. HE 1424−0241, with [Fe/H] ~ -4.0 dex, breaks this paradigm. It is a many σ outlier in several of the abundance ratios, with $\epsilon(\mathrm{Si})/\epsilon(\mathrm{Fe}) \sim 1/10$ and $\epsilon(\mathrm{Si})/\epsilon(\mathrm{Mg}) \sim 1/25$ that of all previously known EMP giants or dwarfs, but normal [Mg/Fe]. It also has a moderately large deficiency of Ca and a smaller deficit of Ti, combined with enhanced Mn and highly enhanced Co, both odd atomic number elements. With respect to Fe, C is normal or low in HE 1424−0241 (the G band of CH was not detected), and the heavy neutron capture elements are low.

From the point of view of SN II nucleosynthesis, HE 1424−0241 is deficient in the explosive α-elements but has a normal [Mg/Fe] ratio, where Mg is produced in hydrostatic α-burning. Recent models of production yields in SNe II fail completely to reproduce the behavior of the α-elements in HE 1424−0241, whose chemical inventory presumably resulted from a very small number of previous SNe II combined with any contributions from a hypothesized Population III. They also fail to reproduce the large excess of Co with respect to Fe. These predicted yields are sensitive to the mass cut, to the adopted electron excess profile, and to other explosion characteristics assumed in the calculations for model SNe. They presumably were tuned to reproduce the behavior of the previously known EMP stars, so their failure to come close to reproducing the highly anomalous abundance distribution in HE 1424−0241 is perhaps understandable.

HE 1424−0241 thus provides important clues as to the details of SN II explosions and their nuclear production yields. It is so metal-poor that no explanation other than unusual core-collapse SN nucleosynthesis yields can be invoked to explain its unique abundance ratios. Modifications to standard SN II models will need to be made to find explosion parameters that can reproduce the properties we have derived for the peculiar EMP giant HE 1424−0241.

We are grateful to the many people who have worked to make the Keck telescope and HIRES a reality and to operate and maintain the Keck Observatory. The authors wish to extend special thanks to those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests. Without their generous hospitality, none of the observations presented herein would have been possible. This publication makes use of data from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, funded by the National Aeronautics and Space Administration and the National Science Foundation. J. G. C. is grateful to NSF grant AST-0507219 for partial support. N. C. is a Research Fellow of the Royal Swedish Academy of Sciences supported by a grant from the Knut and Alice Wallenberg Foundation. He also acknowledges financial support from Deutsche Forschungsgemeinschaft through grants Ch 214/3 and Re 353/44.

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